Augmented Reality Tower Technology Flight Test

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ABSTRACT

Augmented reality technology adapted for air traffic control tower applications was used to track an OH-58C helicopter in proximity to an airport. A camera and 'see-through' display system was used to measure the registration error of static airport features and dynamic test aircraft. The observed registration errors of the test aircraft were largely attributable to two terms of error: 1) aircraft surveillance transport latency, and 2) registration error (from all sources) of the static environment. Compensating for registration errors of static objects and modeling aircraft movement reduces registration errors for dynamic (aircraft) objects to ≤2° of error for aircraft-surveillance transport latency ≤ 5 seconds, and to ≤1° of error for transport latency ≤ 2 seconds.

Keywords

Augmented Reality, Air Traffic Control Towers, ADS-B, Flight Test. Static Registration, Dynamic Registration, Head Mounted Display.

INTRODUCTION

Air traffic control Towers suffer visibility impairments during inclement meteorological conditions that negatively impact airport arrival rates, airport departure rates, terminal-area acceptance rates at en-route coordination-fixes, traffic flow management constraints, and surface vehicle accidents, including runway incursions [1][3]. There is no validated method for fully mitigating the operational impact of impaired Tower controller visibility. This technology gap is challenging for both current traffic management operations and the Next Generation Air Traffic System (NextGen) requirements for equivalent operational capabilities in all meteorological and visibility conditions [14].

Several independent research activities have proposed designs that use head-worn, head-tracked, see-through display sub-systems to enhance Tower controllers' situation awareness [15][16][17][18][19]. Most of these proposals were influenced by previous research in three-dimensional displays developed for display of traffic information to the pilot [7], air traffic simulation [3][8], and flight deck avionics [1][13].

This paper reports results of flight test evaluations of the registration performance of an engineering model for real world airfield static objects (e.g., hangars), and dynamic objects represented by the test aircraft. The two principal sources of registration error for aircraft operating in proximity to the airfield are identified, and a simple algorithm is proposed for reducing this error to ≤ 1° when tracked by Automatic Dependent Surveillance-Broadcast (ADS-B), and ≤ 2° for aircraft tracked by current-technology Airport Surveillance Radar.

BACKGROUND

Previous studies [11] have identified large fuel savings and ancillary economic benefits if a system could be implemented that would insure stable rates of airport capacity in all visibility conditions. A system capable of maintaining the safety and efficiency of surface operations during adverse visibility would produce a variety of benefits. These studies also concluded that higher average airport arrival rates would enable more uniform and productive en route and traffic flow management (TFM) operations. The increased surface capacity reliability would improve metrics for taxi-times, departure queues, ground-delays, ground-holds, and cancellations. Their theoretical low-visibility Tower display was required to provide equivalent situation awareness to a clear 360° field of regard, encompassing the airport surface and all approaches and departure areas in the Class-D airspace.

Although various analysts may have estimated the benefits of an effective low-visibility tower tool, they rarely specified how such tools would be designed and operated [12]. One approach proposes using augmented reality technology to achieve the desired functionality [22]. *Augmented reality* (*AR*) refers to the generation of 3D graphics or other media such that they are overlaid on and registered with surrounding objects in our environment. AR differs from virtual reality insofar as AR allows users to view the 'real' world along with superimposed or composited computer-generated displays [10].

NASA, with FAA support, developed several AR Tower Technology (ARTT) engineering prototypes which employed a variety of head-tracking see-through head-worn display systems, for the purpose of exploring the potential of AR technology to enhance Air Traffic Control (ATC) Tower controllers' situation awareness and performance [19][20]. Field evaluations by Moffett Field ATC Tower

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controllers of the initial ARTT prototypes were reported in a NASA Technical Memorandum [21].

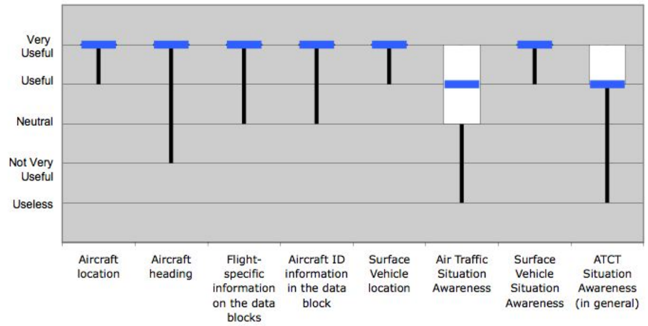

Figure 1. Information Acquisition Question: 'How useful would ARTT technology be in acquiring the following information?'

The controllers opined that AR technology could be 'Very Useful' or 'Useful' in many ATC Tower (ATCT) tasks and duties, acquiring information regarding aircraft location, heading, data-block details, and surface vehicle location and air traffic and Tower situation awareness (Figure 1.).

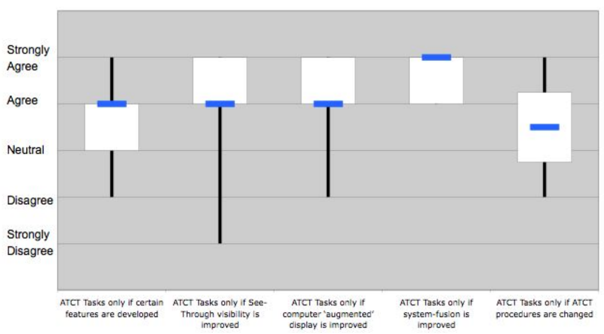

Figure 2. Controller's responses to 'only if' questions indicative of their criticism of AR performance issues.

AR technology maturity issues were addressed by questions with the form: "AR technology would be useful in performing the ATCT tasks ***only if***:" "system-fusion is improved," "computer 'augmented' display is improved," "see-through visibility is improved," "certain features are developed," or "ATCT procedures are changed." (Figure 2.).

The controllers generally criticized the specific performance, comfort, and vision-impairment issues exhibited by the rudimentary ARTT prototypes. They particularly disapproved of the observed registration errors between the ARTT graphical symbol representing the calculated apparent position of the aircraft, and the actual observed position of the aircraft (which were often ≥ 4°), and expressed a preference for reduction of these errors to ≤ 1° or 2° before they could have confidence in using such systems operationally.

The controller responses were employed in subsequent refinement of the ARTT prototypes. In 2008, a flight test was conducted to measure the registration errors associated with aircraft (the most important dynamic objects to ATC) and airfield structures such as hangars and runways (the most relevant static objects).

EXPERIMENTAL DESIGN

The focus of this flight test was to use ARTT engineering prototypes to measure registration errors of real-world airfield static objects and dynamic objects [2][5][6][9][22] represented by a test aircraft tracked by surveillance systems that include both current conventional Terminal radar and the prospective NextGen system, ADS-B.

One test hypothesis proposed that most registration errors of dynamic aircraft objects were caused by two factors: 1) surveillance sensor (e.g., ADS-B) transport latency, and 2) registration error inherited from misregistration between the non-moving (static) environment and its graphical representation, such that compensation for these two error terms may reduce measurable unexplained dynamic error to ≤ 1°.

MATERIALS & METHODS

The NASA ARTT engineering models were composed of five (theoretically independent) sub-systems: a 3D visual database of the surrounding physical environment, traffic management information showing aircraft and surface vehicles, a head motion and orientation tracker to determine the controller's point of view, a real-time computer graphics system to render the synthesized scene combining physical environment with vehicular traffic, and an optical–see-through display. These five subsystems are required to present a virtual world of digital information that is optically combined with the controller's view of the real world.

The registration errors of static airport objects and dynamic aircraft were determined from direct comparison of the computer graphic indication in ARTT and the actual line-of-sight position of the vehicle. A high-performance digital camera collected test data by recording the optical view through the ARTT see-through display. Sufficient graphical and alphanumeric information was included in each captured digital photographic (JPEG) image to measure the offset between the predicted graphical representations and the actual optical images of vehicle and environment.

The ARTT experimental apparatus was designed to facilitate the measurement of inaccuracies and errors. Machine-vision error-correction techniques were eschewed during the data collection phase. We also chose to compare the projected CGI position of the aircraft and the actual optical image of the aircraft, as opposed to using video–see-through AR technologies in which the real-world objects are rendered by real-time digital video.

The ARTT engineering models were designed, assembled, and tested at NASA Ames Research Center. The tests described below were conducted from the Moffett Field Fire Station observation tower, a site with a commanding view of the airfield.

The ARTT systems used in this flight test consisted of three principal functional subsystems: Information Infrastructure, Real-time ARTT, and the Test and Evaluation environment.

Information Infrastructure

The ARTT information infrastructure is illustrated under the blue top rectangle in Figure 3.

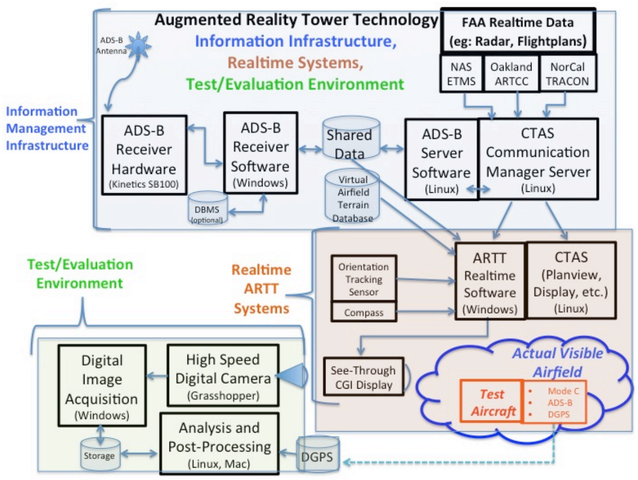

Figure 3. Block diagram of the principal functional components of the ARTT systems described in this paper.

Real-time air traffic data. Real-time ADS-B data was acquired from a Kinetic Avionic Products (hobbyist) model SBS-1 receiver. The SBS-1 received ADS-B data directly from the transmitting aircraft, which was processed by Kinetics proprietary software, and then served to client applications. This ADS-B server infrastructure often exhibited transport latencies of > 2 seconds between ADS-B transmission time and ARTT application reception time.

Real-time FAA Northern California Terminal Radar Approach Control (TRACON) (NCT) air traffic information. This information provided data on aircraft positions, altitudes, velocity, vertical speed, heading; and flight plan information on aircraft ID, aircraft type, equipage, destination, origination, and waypoints.

Additional FAA air traffic real-time data sources, including Oakland (ZOA), Air Route Traffic Control Center (ARTCC), and Enhanced Traffic Management System (ETMS). Local FAA operational real-time data were routed from California to the FAA Technical facilities in New Jersey, which then securely served the data to NASA Ames Research Center via Center TRACON Automation System (CTAS) infrastructure. Selected CTAS subsystems (e.g., Communication Manager) were used to ingest, record, and serve this data to ARTT applications.

Real-time ARTT Systems

The Real-time ARTT subsytems are illustrated under the tan right-center rectangle in Figure 3.

Monocular optical see-through display. We used a Liteye LE-750a 800×600 resolution optical see-through color OLED display with 70% transmissivity and a maximum luminance of 300 cd/m^2 (later replaced with a Liteye LE-500 with nominally identical specification when the LE-750a failed). A neutral density filter was attached to the display to mitigate the displayed image from washing out in the bright sunlit conditions of the observation tower.

Tracker. An InterSense InertiaCube3 hybrid inertial-magnetometer 3DOF orientation tracker was rigidly mounted on the camera assembly to track it, offset from the camera to minimize electromagnetic interference. Because of budgetary limitations, this 3DOF orientation tracker was used instead of a full 6DOF position and orientation tracker, and 3DOF position was determined from site surveys, as described below. A theodolite was used to determine angular measurements of observable features.

ARTT software. NASA ARTT prototype software, which includes a custom 3D model of Moffett Field airport structures, was run on an Alienware Area-51 m17x laptop computer. The ARTT software used a static 3DOF position computed from survey maps and received the dynamic 3DOF orientation input from the InterSense InertiaCube3, run through AuSim AST software. The video output from this laptop was used to drive the Liteye display.

Test and Evaluation Environment

The ARTT information infrastructure is illustrated under the green bottom-left rectangle in Figure 3.

ARTT Data Collection. The ARTT software generated data frames (nominally at 30Hz) that indicated the calculated apparent position of the aircraft (i.e., the virtual aircraft) and the projected graphical representation of the airfield terrain (e.g., runways and hangars). These data frames also contained alphanumeric information, including compass rose (indicating degrees of arc), a vertical scale (also in degrees of arc), a display indicating precise horizontal and vertical angular position of a computer-graphic crosshair, user-interface settings, and state information (e.g., point-of-view position, both latitude/longitude and FAA Center coordinates; and orientation-sensor Heading, Roll, and Pitch), and other experimentally relevant information. Each data frame also recorded the settings of the compensatory slew, match, and lock software that agnostically corrected static registration errors by enabling rapid *x-y-z* and zoom adjustments of the projected virtual terrain to visually match the observed actual terrain. When static registration errors were reduced by slew, match, and lock adjustments, the reduction in static registration errors proportionately reduced the apparent registration errors between the actual aircraft and the virtual position symbol. Each data image captured by the digital camera recorded data on each of these three terms of error: ADS-B latency is expressed as the difference between the ADS-B timestamp and the timestamp of the computer-generated ARTT graphical and alphanumeric data.

Camera assembly. Point Grey GRAS-20S4C-C 2.0MP Color Grasshopper Firewire 1394b camera, rigidly mounted relative to the Liteye see-through display with a Lumicon LA3040 Universal Digicam adapter, supported by a tripod.

Video recorder. The Firewire video output from the Point-

Grey GRAS-20S4C-C camera was connected to and recorded on a Sony Vaio laptop computer. JPEG images were encoded at ~90% compression under the Radius codec and recorded at a user-selected rate of between 8–30 frames per second.

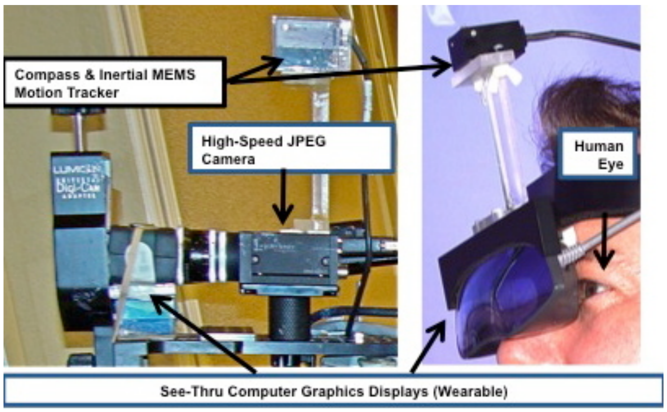

Figure 4. Instrumentation. (left) See-through display, camera assembly, and orientation tracker, compared with (right) previous ARTT engineering model worn by a Moffett Field Tower controller.

ARTT Screen Calibration: Computations made using imagery of Moffett Field obtained from Google Earth (dated June 30, 2007), and consistent with theodolite measurements made inside the Moffett Field Fire Station observation tower, indicate that the distance from the observation tower to the NW corner of Hangars 2 and 3 is approximately 781 m and that the interior of the observation tower measures approximately 5.5 m along its N–S axis. Thus, if tracking an aircraft at the NW corner of Hangars 2 and 3, and assuming the position error of the ARTT infrastructure itself is limited to 5.5 m perpendicular to a target at 781 m, this corresponds to a worst case angular error of $\arctan(5.5/781) = \sim 0.4°$ yaw. (Note that the RMS accuracy of the InterSense InertiaCube3 is specified by the vendor as 1° yaw and that the 1 m mean positional error of the test vehicle corresponds to ~.07° at that distance.) The Liteye 800×600 resolution LE-750a and LE-500 displays are each claimed to have a nominal ~22.4° horizontal field of view (28° diagonal field of view). However, measurements of the displays indicated a horizontal field of view of between ~26°–27°, corresponding to 0.033°–0.034° subtended horizontally per pixel (~30.8–29.6 pixels per degree). The ARTT screen was calibrated using these measurements.

Additional sources of error within the test environment included:

- Inaccuracies in the ARTT Moffett Field 3D airport model
- Effects of static and dynamic environmental metal and electromagnetic signals in the observation tower on the InterSense InertiaCube3
- Errors in the ATC system surveillance data
- Delays between measuring position on the vehicle
- Delays communicating position data to ARTT
- Processing data for display
- Insufficiently rigid mounting of the tracker relative to the display
- Inaccurate measurement of the relative orientation of the tracker and display.

Test Aircraft: The primary test vehicle was an OH-58C owned and operated by the US Army. This vehicle was equipped with three different position and state tracking systems. The first system was a standard Mode-C transponder. The second system was an Ashtech differential GPS (DGPS) receiver, with a mean positional error of <1 m. This receiver recorded positional information at 5 Hz via an onboard laptop computer. The DGPS data was used to establish positional 'truth' in comparison to the ADS-B and TRACON data.

The on-board ADS-B transmitter was a custom pallet containing a Garmin GDL 90, a remote-mounted product that contains a GPS/WAAS receiver and a Universal Access Transceiver (UAT). The GDL 90 transmits ownship data via the UAT data link. It receives data from other UAT-equipped aircraft, as well as FIS-B weather.

Army test pilots repeatedly executed a series of defined test segments to create the test conditions required to satisfy the test matrix. The test points and number of runs performed in the baseline flight test conformed to typical maneuvers performed by helicopter in the terminal area, specifically: Hovers at three altitudes (<100 ft, ~1500 ft, and >1500 ft & < 2500 ft), Approach, Departure, Taxi, Maintained speed runs (10 kts, 40 kts, and 80 kts), Minimum Power Acceleration, Maximum Power Acceleration, and Gradual Deceleration.

RESULTS

Anecdotally, one of the most common experiences during these tests was often losing visual track of the helicopter (a small aircraft with an effectively stealthy visual aspect), and yet locating it via the ARTT apparatus. There were often times when the visual image of the aircraft was not readily detectable, and the ARTT CGI virtual aircraft provided useful indication of the low-visibility aircraft's location.

Dynamic registration (e.g., panning camera) of both static objects (e.g., runways) and dynamic objects (aircraft) often exhibited > 2° error. The dynamic registration (i.e., changing point of view) performance issues were largely (though not entirely) attributable to the orientation sensor and compass tracking performance issues. In most cases, it was necessary to use the ARTT user interface to slew and scale the graphical virtual environment to achieve accurate static registration (fixed, non-moving POV) of static objects (e.g., hangars) before each set of trials, and often it was necessary to make such adjustments during the session.

The preliminary results indicate that static (fixed POV) registration of the virtual aircraft symbol and the image of the actual aircraft may achieve an angular error of ≤ 1° if: (1) the static registration of static objects is first set to ≤ 1°, and (2) ADS-B processing latency is < 0.3 second. Such events, however, were rare. In most cases, ADS-B latency was > 1 second, and horizontal registration (both static and dynamic) of static objects was ≥ 2°.

It was found that in all three Hover conditions (<100 ft, ~1500 ft, and >1500 ft & <2500 ft), the apparatus (after the gross adjustments described above) could demonstrate a maintained (>10 second) tracking error of < 2° between the CGI indicator and the apparent optical image of the helicopter. In these hover tests, the dynamic object effectively imitates a static object.

It was demonstrated in Approach and Departure trials, that static registration (e.g., non-moving camera) of dynamic objects (e.g., aircraft) with tracking errors of < 2° could be achieved using both ADS-B and TRACON ASR-9 radars for surveillance. The noticeable difference between the two surveillance technologies in these cases is that ASR-9 tracking deteriorated when the aircraft was < 2 nmi from the observation point, and the farther the aircraft was from the observer, the greater the agreement between the ADS-B and ASR-9 indicators. This discrepancy between the two surveillance systems is largely attributable to the higher update rate of ADS-B (1 second) in comparison to the slower update rate (4.8 second) of ASR-9.

The other tests (Taxi, Maintained Speed, Minimum Power Acceleration Maximum Power Acceleration, and Gradual Deceleration) demonstrated that although certain frames in each test sequence could achieve static (non-moving POV) registration of aircraft (dynamic objects) with ≤ 2° error across multiple frames, there were also more incidents of frames in each sequence where the optical and CGI aircraft position error were > 2°. These errors tended to become more pronounced when the aircraft was < 0.5 nmi from the observer position.

In addition to the Army's OH-58C, other aircraft equipped with ADS-B were also observed for less formalized tests, including a B-767-200. The behavior of the ARTT prototype with these fixed-wing aircraft was similar to that with the test helicopter.

ADS-B transport latency is defined (for the purposes of this study) as the time difference between the transmission of the ADS-B signal by the aircraft and the rendering of the ADS-B data by ARTT into a CGI error. This particular source of error might be mitigated by more sophisticated ADS-B receivers (which were beyond the budget for this experiment); however, one beneficial upshot of the occasionally excessive ADS-B processing latencies was the ability to simulate similar issues that may be encountered when real-world aircraft surveillance systems perform anomalously. Latency was measured as the difference between the JPEG data image ADS-B timestamp and the frame generation timestamp, as illustrated in Figure 5.

The other major source of dynamic object registration error was inherited static object misregistration (from all causes). This type of error may be attributable to congruence inaccuracies in the ARTT prototype's visual database of the airfield, difficulty of accurately determining the exact position of the viewer, and other potential error sources. The inertial tracking and compass sensor often contributed the greatest amount of registration error, due to its intermittent latencies, environmental sensitivities, and inherent inaccuracies. These sensor-involved errors (unsurprisingly) were often more pronounced when the apparatus was dynamic (e.g., camera panning) than when it remained fixed on the tripod with a static orientation. In some cases, the orientation tracker errors were counterintuitive, overcompensating for apparent motion in the opposite direction from the panning motion.

Data collected from a trial where the aircraft flew at low altitude above the runway at a sustained speed of 80 kts, followed by a deceleration, is illustrated in Figure 5. The edges of the ARTT-rendered CGI virtual graphic hangars extend 2.8° to the left of the actual real-world hangers, documenting −2.8° horizontal misregistration of static (non-moving) objects in that particular data image. Since the entire virtual environment is shifted left by 2.8°, the ARTT real-time CGI virtual aircraft symbol (concentric squares surrounding a white dot) is also shifted by −2.8°. Adding 2.8° (in this case) to the virtual aircraft's horizontal position effectively compensates for misregistration artifacts inherited from the registration error associated with static objects.

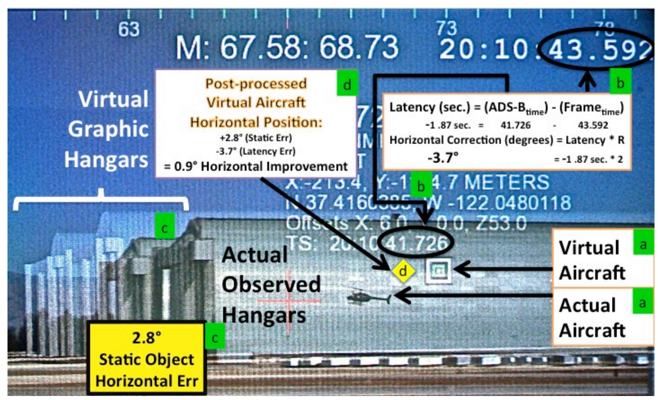

Figure 5. ARTT data image, illustrating: (a) apparent registration error of dynamic object (test helicopter); (b) sensor transport latency, defined as the difference between the ADS-B timestamp and the ARTT CGI timestamp; (c) registration of static objects (e.g., hangars); and (d) registration error reduction by subtracting the sum of static and latency horizontal errors from the virtual aircraft horizontal value.

The best method of eliminating misregistration of static objects would require a system for tracking orientation without artifact or error. One method (among many) for improving registration of static objects is to measure the misregistration in each combined image and use that information to calculate an improved solution [4].

The effect of a simple corrective algorithm that compensates for these two sources of error is illustrated in Figure 6, which depicts data from a trial where the test aircraft flew at low altitude above the runway at a sustained speed of 80 kts, followed by a deceleration. This data portrays a sequence of events during which the ARTT ADS-B subsystem exhibited excessive transport latency (> 6 seconds in the worst case).

The horizontal registration error of static objects varied from highly accurate registration to > 6° mismatch.

This test data illustrates how observed misregistration of the dynamic object (i.e., virtual vs. actual aircraft position) is largely attributable to the sum of surveillance latency and static object registration error.

One Moffett Field Tower controller "rule of thumb" is that high-speed taxiing aircraft on the more distant runway (~ 0.4 nmi distant) will subtend ~ 2° horizontal translation (approximately the width of a thumb held at arm's length) per second. This heuristic provides a simple (though obviously improvable) method of estimating the horizontal angular error engendered by ADS-B latency for the purposes of the following discussion.

The efficacy of subtracting these ADS-B latency and static registration horizontal excursions from the unfiltered virtual aircraft position is illustrated in Figure 5. In this case (as noted above), the edge of the misregistered virtual hangar extends 2.8° from the corresponding edge of the actual hangar, and the ADS-B latency contributes a −3.7° error (in the opposite direction). Since the sum of these two errors is −0.9°, the post-processed virtual aircraft symbol is reset 0.9° to the right of the ARTT-generated virtual aircraft. The resultant position shift reduces the observed dynamic registration error from 2.6° to 1.7°.

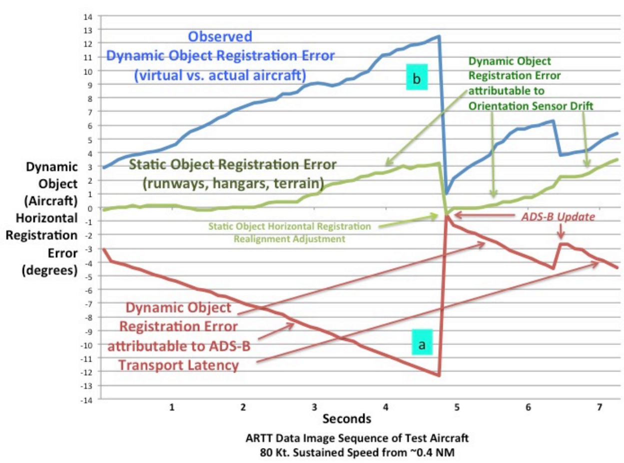

Figure 6. Registration error of dynamic object is a variable largely dependent on the summed registration errors generated by (a) effects of ADS-B (aircraft surveillance) latency and (b) static object registration errors (all causes). When the ADS-B broadcasts new updates, latency error is sharply reduced. User adjustments to correct static-object registration error similarly improves dynamic-object registration.

This filter algorithm may be more formally stated as:

$P_{Filtered} =$

$P_{Unfilterd} - ((V_{Terrain} - A_{Terrain}) - (R*(S_{Timestamp} - G_{Timestamp})))$,

where

$P_{Filtered}$ = Filtered Virtual Aircraft Symbol horizontal position (compass degrees of arc),

$P_{Unfiltered}$ = Unfiltered Virtual Aircraft Symbol horizontal position (compass degrees of arc),

$V_{Terrain}$= Virtual Terrain = Edge of Virtual Terrain object X value (compass degrees of arc),

$A_{Terrain}$ = Actual Terrain = Edge of Actual Terrain object X value (compass degrees of arc),

R = Aircraft apparent horizontal angular speed rate (degrees of arc per second); in this case, heuristically set to a constant 2 (see text),

$S_{Timestamp}$ = Surveillance update timestamp (in this case from ADS-B), and

$G_{Timestamp}$ = ARTT graphical frame-generation timestamp.

Figure 7. illustrates how this simple filter scheme reduces horizontal registration errors for dynamic objects (aircraft) .

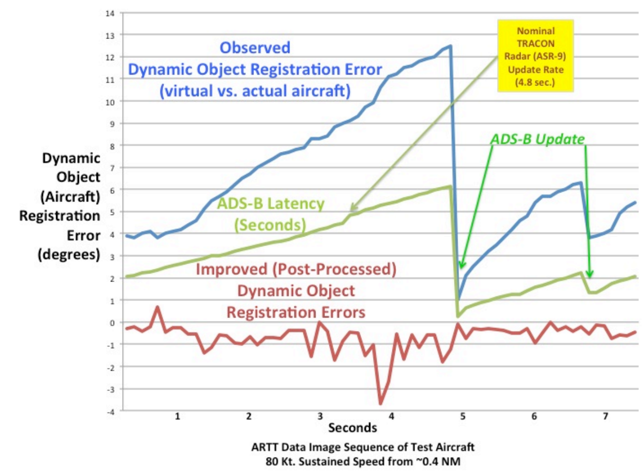

Figure 7. Observed dynamic registration accuracy may be improved by subtracting static registration and sensor-latency errors from unfiltered virtual aircraft symbol position.

Error is reduced to ≤ 1° in cases where surveillance transport latency is < 2 seconds (subtending a ~ 4° error). Since 2 seconds latency is within the expected NextGen System Wide Information Management ADS-B performance, sub-degree ARTT aircraft registration under these conditions accuracy should be achievable. In cases where surveillance transport latency is < 5 seconds (subtending 10° horizontal error), the horizontal registration error is reduced to ≤ 2°. Since the ASR-9 update rate is 4.8 seconds, horizontal accuracies of ≤ 2° should therefore be achievable with conventional Terminal radar systems.

The simple filter proposed in this paper has two principal flaws. The term for the apparent horizontal angular speed rate of the aircraft was heuristically set to a constant 2° per second, upon recommendation of a Tower controller who knew from experience that this constant works well with aircraft accelerating or decelerating down a runway with an average speed of 80 kts. More sophisticated aircraft speed and routing models should yield better results, though that rich discussion is beyond the scope of the current paper.

CONCLUSIONS

The flight tests described in this paper explore the potential of using AR technology as an ATCT tool that could enable controllers in diminished-visibility conditions to effectively visualize airport static object models and dynamic aircraft objects represented by air traffic surveillance data.

The principal motivation for these tests was to separate speculation from actual observation of the sources and potential mitigation of registration of dynamic objects representing aircraft operating in proximity of an airfield. The results demonstrate that the most significant error of this kind may be attributable to either static object registration error and/or surveillance transport latency. For the purposes of illustration, a simple filter demonstrates how filtering these two terms may reduce aircraft registration error to < 2° with currently deployed Terminal radar systems and to < 1° with the expected NextGen deployment of ADS-B.

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